Available online at www.sciencedirect.com
SCIENCE DIRECT®
Fisheries Research 76 (2005) 344–358
FISHERIES RESEARCH
www.elsevier.com/locate/fishres

Preliminary assessment of the Falklands Patagonian toothfish (*Dissostichus eleginoides*) population: Use of recruitment indices and the estimation of unreported catches

Adam G. Payne [a,*], David J. Agnew [a], Anabela Brandão [b]

[a] *Renewable Resources Assessment Group, Department of Environmental Science and Technology, Royal School of Mines, Imperial College, Prince Consort Road, London SW7 2BP, UK*
[b] *Department of Mathematics and Applied Mathematics, University of Cape Town, Private Bag, Rondebosch 7701, South Africa*

Received 12 January 2005; received in revised form 13 July 2005; accepted 27 July 2005

Abstract

Longline fishing for Patagonian toothfish (*Dissostichus eleginoides*) has taken place in Falkland Island waters for over 10 years. This species was previously only caught as bycatch in the *Loligo gahi* and finfish trawl fishery. This paper presents a preliminary assessment of the Falkland Islands population of *Dissostichus eleginoides* using an age-structured production model (ASPM). Two models were investigated; one using a Beverton–Holt stock recruitment relationship and another using trawler CPUE based estimates of toothfish abundance to estimate yearly recruitment. A stock recruitment relationship was not included within the model that used abundance estimates, as recruitment to the population was estimated directly from the index of relative recruit abundance calculated from trawler CPUE. The model was fitted to longline standardised CPUE and to the catch-at-length data. The models produced estimates that provided similar declines in the toothfish population although the start and end biomass estimates varied slightly. The models provided estimates of between 13,000 and 26,000 tonnes of current spawning stock biomass and showed current biomass to be between 38 and 46% of virgin biomass. The fit to CPUE was poor between 1994 and 1996, which we hypothesised could have been due to unreported catches or changes in q or M. This was a time when there was considerable IUU fishing in the southwest Atlantic. When the model was allowed to estimate a level of extra catch the fit was improved and 5000 tonnes of extra catch was estimated. Two further models were briefly examined to investigate the possibility of changes in M and q but both required large changes in those parameters in order to fit. Estimates of MSY varied widely, from 912 to almost 3000 tonnes.

Keywords: Patagonian toothfish; *Dissostichus eleginoides*; Age-structured production model; Stock size; Recruitment index; Unreported catch estimation

1. Introduction

The Patagonian toothfish, *Dissostichus eleginoides* (Smitt, 1898), is a long-lived and slow growing

* Corresponding author. Tel.: +44 20 7594 7310; fax: +44 20 7594 7310.
E-mail address: a.payne@imperial.ac.uk (A.G. Payne).

0165-7836/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.fishres.2005.07.010

notothenid fish, endemic to Antarctic and sub-Antarctic waters (Agnew, 2004). Toothfish mature at over 10 years of age and can attain sizes of 2 m or more (Everson and Murray, 1999). This slow growth and high age at maturation makes the Patagonian toothfish extremely vulnerable to over exploitation and, thus, it is of utmost importance that an understanding of its population size and dynamics is obtained. Patagonian toothfish are caught between depths of 200 and 2000 m on the continental shelf slope around South America and the Falkland Islands, and can be found down to almost 4000 m (Agnew, 2004; Froese and Pauly, 2005). Toothfish appear to spawn at depths of between 800 and 1000 m (Agnew et al., 1999) and have a larval phase of several months (Kellerman, 1990; North, 2002). The juveniles settle at a length of 12–15 cm at depths of between 150 and 400 m, remaining there until they reach a size of approximately 60–70 cm, whereupon they move into deeper water (Eastman, 1993).

Nowadays it is an important and highly valuable fish, with a reported global catch between 1995 and 2000 of between 28,035 and 44,047 MT annually (FAO, 2002) and a value of up to US$ 9000 a tonne (González and García, 2001). Commercial longline fishing began around the Falkland Islands in 1994 (with some experimental fishing in 1992 and 1993) and has yielded, on average, 1500 tonnes of toothfish a year (Falkland Islands Government, 2004). Prior to 1992 toothfish were mainly caught as a bycatch in the trawl fishery for *Loligo gahi* and other targeted finfish (e.g. southern blue whiting, *Micromesistius australis*) and yielded on average 400 tonnes per annum (Falkland Islands Government, 2004). A Falkland Islands longline fishery started to target adults in deep water (>600 m) from 1992 onwards, and large scale fishing also started in Argentine waters at this time.

The trawl fisheries for *Loligo gahi* squid and other finfish catch mostly juvenile and some adult toothfish as bycatch, usually in depths less than 500 m (Falkland Islands Government, 2004). Thus, these catches have potential as indicators of recruitment by using the CPUE from the trawler bycatch or swept area measurements of juvenile abundance as indices of recruitment. These recruitment estimates could be incorporated into a population model as either relative or absolute estimates of the number of toothfish recruits in a given year.

Our assessment assumes that the Falkland Islands stock of toothfish is effectively discrete. Although it is possible that populations inhabiting both Falkland and Argentine waters are part of the same population (Shaw et al., 2004), two discrete spawning and juvenile areas are known. Within Falkland waters, spawning animals regularly appear around the Burdwood Bank in July to September (des Clers et al., 1996), with juveniles appearing around the Falkland Islands. The second spawning ground is south of Staten Island to the south of Argentina (Prenski, personal communication), with juveniles appearing to the east and north of Staten Island. As toothfish appear not to be highly migratory (DeWitt et al., 1990; Williams et al., 2002; Møller et al., 2003) it may be a reasonable starting assumption that these latter animals recruit to the Argentine fishery (on the shelf and on the southern edge of Burdwood bank) and the former recruit to the Falkland Islands fishery.

An unsuccessful attempt to assess the Falkland Islands toothfish population using a DeLury depletion method on very localised areas was made by des Clers et al. (1996). At the time there were insufficient data to undertake an age-based, fishery-wide population model; a situation that has since been rectified. A variety of other assessment methods have been used for toothfish: mark-recapture (Macquarie Island: Tuck et al., 2003; South Georgia: Agnew and Kirkwood, 2004), forward projection of juvenile biomass (Heard Island: Khalid and de la Mare, 1996; South Georgia: Agnew, 2004), and age-structured production models (Prince Edward Islands: Brandão et al., 2002a). An attempt has also been made to estimate adult densities using baited cameras (Yau et al., 2001).

In this study an age-structured production model based on that of Brandão et al. (2002b) has been used to assess the Falkland Islands toothfish population. The model of Brandão et al. (2002b) was applied to a similar population of toothfish at Prince Edward Island. The first model was based on the original model of Brandão et al. (2002b) (henceforth called 'formulation 1'). The second used estimates of abundance from trawler CPUE as an index to estimate annual recruitment instead of the Beverton–Holt stock recruitment relationship in the original model (formulation 2). There were some major discrepancies between observed and predicted CPUE in these models and we examined several different hypotheses for this difference. The results from the models were compared with

the results from the original model of Brandão et al. (2002b) and discussed in the context of sustainability and management of the Patagonian toothfish fishery around the Falkland Islands.

2. Method

Data for this study were collected in Falkland Island waters and on the high seas by fisheries observers onboard licensed longliner vessels between 1992 and 2003, and vessels operating bottom trawls in the finfish and *Loligo gahi* fisheries between 1987 and 2003. Daily reports from both trawler and longline vessels of total catch, position and effort are made to the Falkland Islands Fisheries Department daily. These data were analysed for the period 1987–2003 to estimate temporal and spatial variation in activities of both trawl and longline vessels. Only bottom trawl fishery data were used in conjunction with data from longline vessels. No data collected either from pelagic or semi-pelagic catches were utilised in the analysis or construction of the model.

For the index of abundance of recruits used in formulation 2 a standardised trawler CPUE series was required as this most closely reflected juvenile population dynamics (as trawlers mainly target smaller individuals on the shelf). CPUE data from 1991 to 2003 for the trawl fishery were examined along with vessel data including the area fished, the depth of fishing and the month that fishing occurred. The GLM did not include a nation factor as only data from the Spanish/Falklands fleet was used. The other nations showed inconsistency in catch rates and their duration within the fishery. For the trawler series the data formed a delta-lognormal distribution (as not all hauls or trawls caught toothfish) with many zeros present within the data. This was modelled as a binomial GLM on the probability of a trawl encountering toothfish and a lognormal GLM on abundance for all positive trawls. There were too few data from the areas fished north of Falklands' waters around 46°S to be included in this analysis. The GLM used for standardisation of positive trawler CPUE was given by:

$$\ln(\mathrm{CPUE}) = \mu + \alpha_{\mathrm{year}} + \beta_{\mathrm{month}} + \gamma_{\mathrm{area}} + [\delta + \eta_{\mathrm{depth}} + \theta^2_{\mathrm{depth}}] + \varepsilon \quad (1)$$

where CPUE is the positive toothfish catch in kg/h, μ the intercept, α_{year} a factor with 13 levels associated with the years 1991–2003, β_{month} a factor with 12 levels (January to December), γ_{area} a factor with four levels (North east 52 to 47°S and 59 to 52°W, North west 52 to 47°S and 59 to 64°W, South east 52 to 57°S and 59 to 52°W South west 52 to 57°S and 59 to 64°W), $[\eta + \theta_{\mathrm{depth}} + \varphi^2_{\mathrm{depth}}]$ is the depth at which fish are captured incorporated as a second order polynomial and ε an error term. The probability of recording a positive catch of toothfish was given by:

$$p(+\text{ve catch}) = \mu + \alpha_{\mathrm{year}} + \beta_{\mathrm{month}} + \gamma_{\mathrm{area}} + [\delta + \eta_{\mathrm{depth}} + \theta^2_{\mathrm{depth}}] + \varepsilon \quad (2)$$

The combined estimated CPUE for each year was calculated as a product of the probability of obtaining a positive (non-zero) catch of toothfish and the predicted CPUE of toothfish in positive trawls. The bold parameters are the predicted values from the binomial and Gaussian GLMs:

$$\mathrm{ExpectedCPUE}_y = \boldsymbol{p}(+\textbf{ve catch})_{\boldsymbol{y}}\exp(\ln \mathbf{CPUE}_{\boldsymbol{y}}) \quad (3)$$

In order to calculate the abundance of recruits from the $\mathrm{ExpectedCPUE}_y$ the estimate was separated into a fraction equal to age three (the age at which most fish recruit to the trawl fishery) and another fraction equal to fish older or younger than three. The number of 3-year-olds per hour was estimated by dividing the $\mathrm{ExpectedCPUE}_y$ for 3-year-old fish by the weight of fish at that age. This was then converted to the number of individuals per year by multiplying by the total annual effort for each year. Finally the number of recruits 3 years previously was estimated from the number of 3-year-old fish (Table 1):

$$r_{y,0} = r_{y+3,3}(\mathrm{e}^{3M}) \quad (4)$$

where r is the number of recruits in year y and M the natural mortality.

For the purpose of both models a standardised longline CPUE series was required as this most closely reflected adult population dynamics (rather than trawler CPUE). CPUE data from 1994 to 2003 for the longline fishery were examined along with vessel data including vessel nationality, area fished, depth of fishing and the month that fishing occurred. There were too few

Table 1
Annual catches and index of relative recruit abundance created from trawler CPUE abundance estimates and used in formulation 2

Year	Catches	Abundance index
1988	26	652638
1989	127	172925
1990	236	384423
1991	208	87029
1992	978	53849
1993	912	137518
1994	394	292565
1995	2963	1238662
1996	2069	2745240
1997	686	1045760
1998	1195	1281101
1999	1539	239914
2000	2988	206059
2001	2318	656745
2002	1754	656745
2003	1793	656745

The last 3 years of the index are set as the average of the years between 1988 and 2000.

data from the areas fished along the North Scotia Ridge and areas north of Falklands' waters around 46°S to be included in this analysis. However, out of zone catch data close to the edge of Falklands Conservation Zones were included within the regional classifications, as they were indicative of fishing on stocks within the zone. North and south were distinguished along 53.5°S; this division separates the Burdwood Bank spawning area from fishing carried out further north. Various error models were tested, including a Delta and quasi-lognormal model. None gave particularly good fits (the q–q plots were not completely normalised). A lognormal Gaussian model was chosen as the simplest, with the most normal q–q plot. The GLM used for standardisation of positive longliner CPUE was given by:

$$\ln(\text{CPUE}) = \mu + \alpha_{\text{year}} + \beta_{\text{month}} + \gamma_{\text{region}} + \delta_{\text{nation}} + [\eta + \theta_{\text{depth}} + \varphi^2_{\text{depth}}] + \varepsilon \quad (5)$$

where CPUE is the positive toothfish catch in kg per 1000 hooks, μ the intercept, α_{year} a factor with 10 levels associated with the years 1994–2003, β_{month} a factor with 12 levels (January to December), γ_{region} a factor with two levels separated by 53.5°S (North and South), δ_{nation} a factor with five levels associated with the nations Chile, Falkland Islands, Iceland, Korea and Norway, $[\eta + \theta_{\text{depth}} + \varphi^2_{\text{depth}}]$ is the depth at which fish are captured incorporated as a second order polynomial and ε an error term. The probability of recording a positive catch of toothfish was given by:

$$p(+\text{ve catch}) = \frac{P_y}{H_y} \quad (6)$$

where P_y is the number of positive hauls in year y, and H_y the total number of hauls in year y. The combined estimated CPUE for each year was again calculated as a product of the probability of obtaining a positive (non-zero) catch of toothfish and the predicted CPUE of toothfish in positive hauls (see Eq. (3)).

The CPUE-based ASPM assessment and projections were implemented as in Brandão et al. (2002b) using the AD Model Builder software package. The assessment applied a deterministic ASPM, which assumed that the resource was at its average pre-exploitation level at the time that exploitation commenced. The original model of Brandão et al. (2002a) involved estimating the pre-exploitation spawning biomass (K^{sp}) by maximising the likelihood of the fit of the standardised CPUE to the trend in the exploitable component of biomass as predicted by the ASPM. The model of Brandão et al. (2002b) differed from the previous model of Brandão et al. (2002a) as it used the catch-at-length data from the fishery when estimating the parameters of the ASPM in addition to the standardised CPUE. The model of Brandão et al. (2002b) also estimated the parameters of the logistic selectivity curve while all other input parameters were assumed (Table 2).

Natural mortality on the Patagonian shelf has been estimated as 0.06 (Pauly regression method), through

Table 2
Biological parameter values assumed for the assessments

Parameter	Value
Natural mortality	0.165
Von Bertalanffy growth	
$\ell_{\infty\,(\text{cm})}$	209.7
κ (year^{-1})	0.051
t_0 (year)	−0.14
Length–weight relationship	
a	2.17×10^{-5}
b	3.34
Age-at-maturity (year)	10
Age-at-first capture (year)	3

All of the models use these same parameter values and only estimate K^{sp}, the selectivity curve and illegal catch where appropriate.

0.1–0.12 (Rikhter and Efanov method) (Baranowski et al., 1995) and from 0.132 to 0.198 in CCAMLR Subarea 48.3 (Moreno and Rubilar, 1992; Brandão et al., 2002b; Agnew, 2004). Following Brandão et al. (2002b) a middle value of this range (0.165) was used in our model.

A stock–recruitment relationship was not included in the model using trawler CPUE estimates of recruit abundance as an index (formulation 2). For this model an additional parameter, q' needed to be established to relate recruit population size to the index. Recruitment was then the number of recruits from the relative abundance estimate multiplied by q' (which was estimated by the model) to raise the index to an appropriate level for a recruitment population. The virgin population was calculated from R_0 (recruitment to virgin biomass (see Appendix A)), which in the abundance estimate model (formulation 2) was taken as the first years index number multiplied by q'. The population in each subsequent year was then projected forward from the virgin biomass and the recruitment in each year calculated from the relevant estimate and q'.

Recruitment into the fishery took two different forms, depending on whether a Beverton–Holt stock recruitment relationship or trawler abundance estimate of recruits was used. For formulation 1 a Beverton–Holt stock recruit relationship (assuming deterministic recruitment) was incorporated:

$$R(B^{\mathrm{sp}}_{y+1}) = \frac{\alpha B^{\mathrm{sp}}_{y}}{\beta + B^{\mathrm{sp}}_{y}} \tag{7}$$

Thus, the number of recruits in formulation 2 (replacing Eq. (7)) was given by:

$$N_{y+1,0} = R(B^{\mathrm{sp}}_{y+1}) = q' r_{y+1,0} \tag{8}$$

where $r_{y,0}$ is the index for the year y.

3. Results

The results produced by the two models are given in Table 3 and show that the models varied widely for most estimates. For instance formulation 2 estimated higher R_0, virgin and current biomass than formulation 1. Formulation 2 estimated q' to be 3.85, which indicates that the index needed to be raised by a factor of almost 4 in order to be able to fit the model. Interestingly the MSY estimate from the index model was almost triple the other estimates, which estimated MSY to be between 900 and 1000 tonnes. Formulation 1 demonstrated a reasonable fit to CPUE but failed to replicate the steep decline seen between 1994 and 1995 (Fig. 1a). This model showed a shallow decline until 1994 when the decline became steeper but deviated from the CPUE trend. Formulation 2 showed a similar trend, although the decline after 1994 seemed to increase more rapidly and also showed a slight increase between 2003 and 2004 (Fig. 1b).

Both these models produced a reasonable fit to CPUE in later years, but a poor fit in the earliest years of the series (1994–1996). In the years 1994 and 1995 there was a large amount of IUU (illegal, unre-

Table 3
Result of toothfish assessment from formulations 1–3 including recruitment, biomass estimates and the parameters of the selectivity vector; a_c is the mean age at which 50% of the toothfish are retained in the fishing gear, a_d is the age at which the selectivity vector changes for older fish, δ is the steepness of the selectivity curve and ω is the steepness of the selectivity curve for older fish

	Formulation 1	Formulation 2	Formulation 3
q CPUE	1.50×10^{-2}	1.05×10^{-2}	1.50×10^{-2}
R_0	1420850	2510620	1517750
SSB_0	31904 (S.E.: 2994)	56373 (S.E.: 10857)	34079 (S.E.: 2230)
SSB_{2003}	14056 (S.E.: 2937)	25854 (S.E.: 8163)	13000 (S.E.: 1899)
Ratio (SSB_0/SSB_{2003}) (%)	44	46	38
MSY	912	2832	992
Catch 1994	2963	2963	2963
Catch 1995	2069	2069	6488
a_c	9.000	9.869	9.051
a_d	12	12	12
δ	2.23×10^{-5}	1.045	0.042
ω	0.186	0.233	0.161

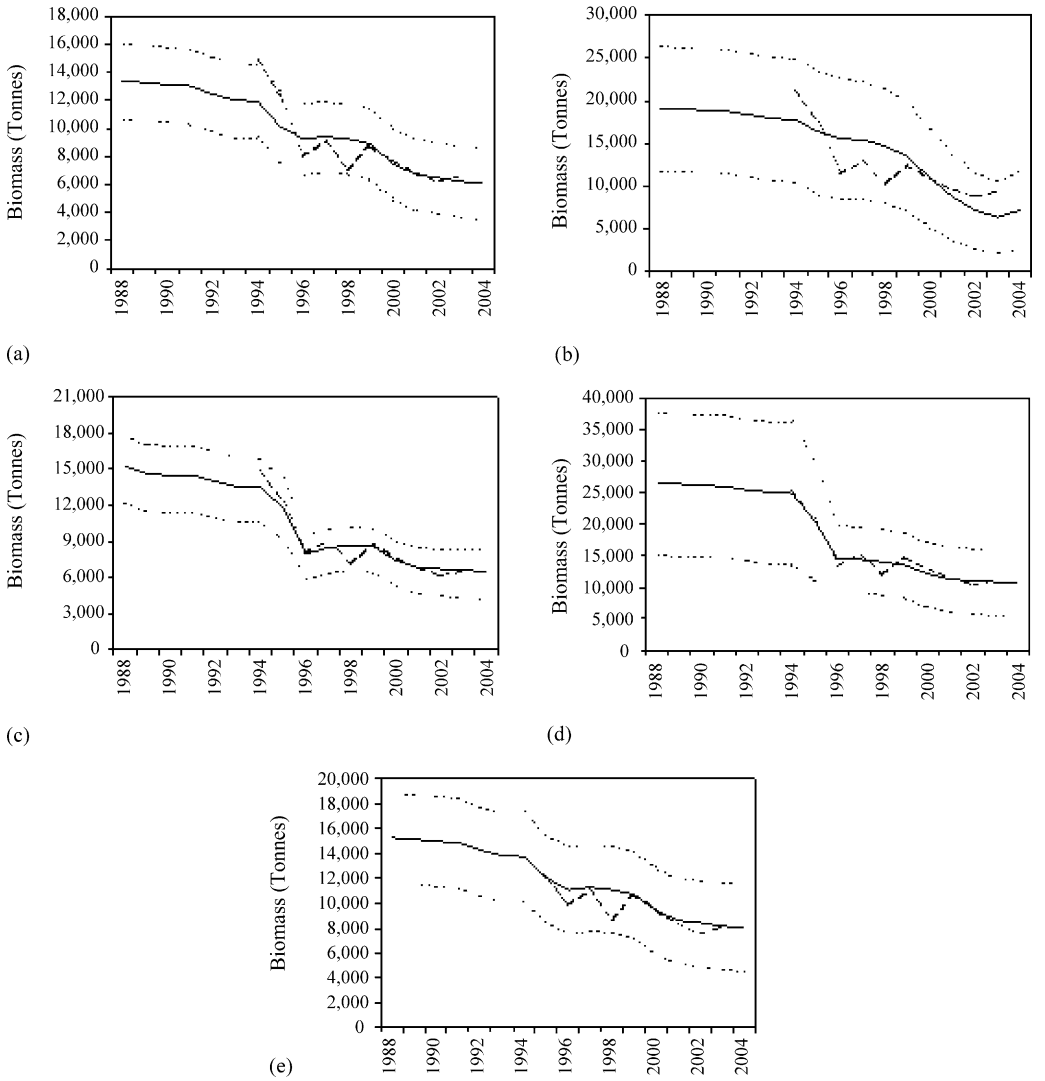

Fig. 1. Fit of CPUE to exploitable biomass for the (a) formulation 1 and (b) formulation 2. (c)–(d) are formulation 1 modified to estimate (c) unreported catch in 1994 and 1995 (formulation 3) with different M (d) in 1994 and 1995 and different q (e) in 1994 and 1995. The complete line represents the exploitable biomass, the CPUE by the dashed line and the dotted lines are the Hessian based confidence intervals.

ported and unregulated) fishing activity in the south-west Atlantic (Agnew, 2000) and increases in catches taken in Argentine waters (FAO, 2002, 2004) were indicative of an increase in effort. This suggested that there might have been some unreported (IUU) catches of toothfish from the Falkland Islands stock, either taken within the Falkland Islands zone or in adjacent high seas waters. To test for this we adjusted formulation 1 to estimate an unknown additional catch in 1994 and 1995 and called this model formulation 3. The result produced a much improved fit to the CPUE trend: a shallow decline before 1994 followed by a sharp and extremely rapid decline between 1994 and 1996, with a shallower decline following between 1996 and 2004. This model showed the best fit to the CPUE trend and estimated almost 5000 tonnes of extra catch in 1995 that was not recorded in Falkland Island waters (Fig. 1c, Tables 1 and 3).

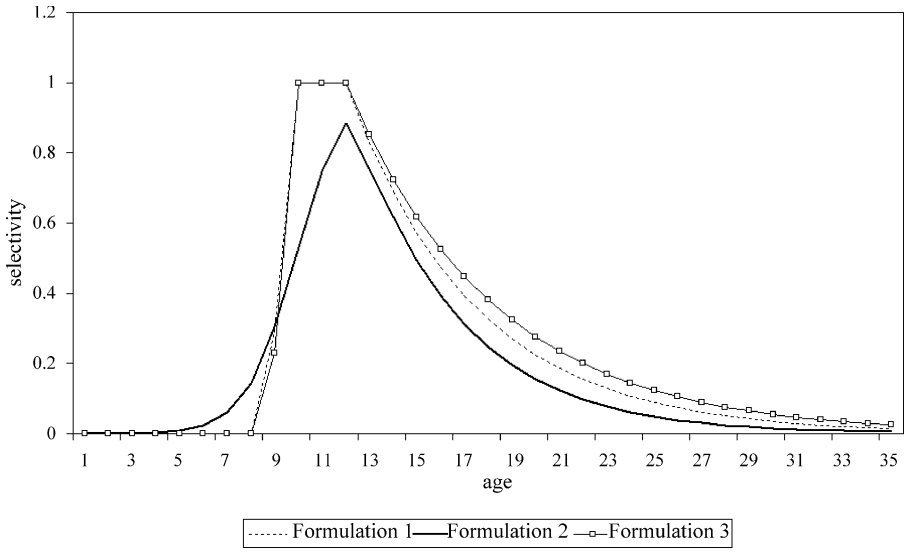

Fig. 2. Toothfish commercial selectivity vectors estimated by formulations 1–3.

Other possibilities were that changes in q, the catchability coefficient, and M, natural mortality could have caused the rapid decrease in CPUE in 1994 and 1995. Two models that estimated separate q and M parameters for 1994 and 1995 were also investigated. Despite producing very good fits to CPUE (Fig. 1d and e) the estimates of both q and M were much larger than the estimates used in the models for the remaining years. The estimate produced for q in 1994 increased to 1.61×10^{-2}, compared to 1.22×10^{-2} estimated for the remaining years. In 1995 the estimate for q was 1.53×10^{-2}. This suggested that more fish were accessible and easier to catch in 1994 and 1995 and after this period fish became less catchable, for which there is very little evidence. As for M, in order to fit the CPUE trend the model estimates of M were 0.284 and 0.473 for 1994 and 1995, respectively. These values represented increases of 72 and 187%, respectively, on the estimate of M used for the remaining years (0.165) and were outside the bounds normally assumed for M in toothfish (0.132–0.198; CCAMLR, 2002).

The selectivity vectors produced by formulations 1 and 3 were almost identical (Fig. 2). However, the selectivity vector of formulation 2 showed a very different trend. Formulation 2 was slightly more selective at an earlier age but peaked at a later age than the other two models without reaching a point at which all fish are caught in a particular age group. However, after the age at which selectivity changes was reached (assumed to be 12 years of age) the selectivity vectors for the original model and formulation 2 became marginally different to each other, with the original model decline being more rapid than that of formulation 3. The result of this was that the fit to length frequency data was pushed slightly to the left in some early years for formulation 2 (Fig. 3) when compared with the original model (Fig. 4). In more recent years the selectivity was pushed more to the left and formed a completely different distribution and it appears that the fits in these years are affected by the selectivity vector more than other years. The fit to length frequency in formulation 3 was very similar to that of the original model (Fig. 5), despite the small difference after the cryptic age was reached.

Overall the fit to catch-at-length data was reasonable, particularly in the years after 1994. This was mainly due to the selectivity vector estimated by the models being for longline fishing rather than as a combination of trawl and longline. This was particularly illustrated by the years 1988–1990 and 1993 where the predictions of catch-at-length were completely different to the observed catch-at-length. In these years (and 1991) all data were collected by observers on board

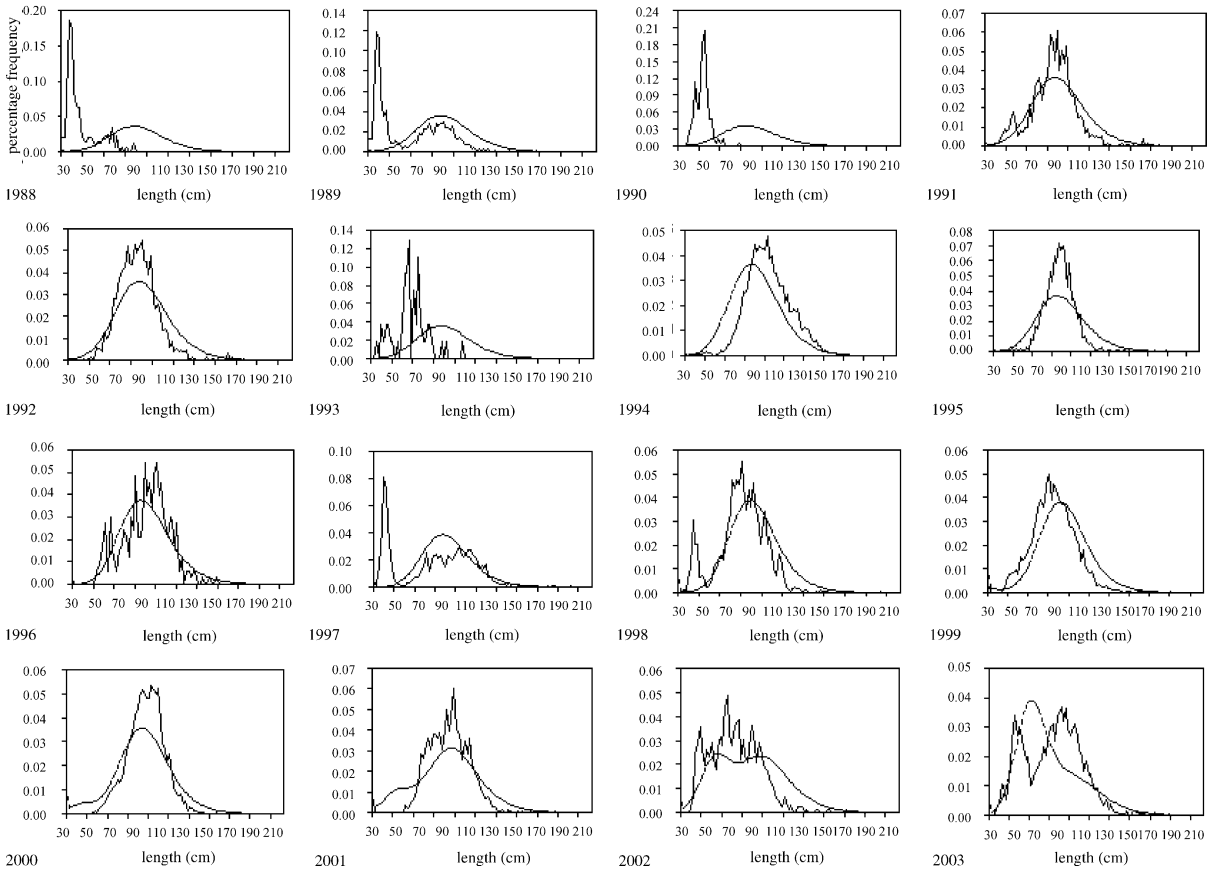

Fig. 3. Observed (solid line) and predicted (dotted line) length frequencies from formulation 2.

trawl vessels and as a result the catch-at-length was composed mainly of small individuals for which the selectivity vector cannot account. In 1997 there was a large peak at smaller sizes, possibly due to a large number of juveniles present in the population or as a result of a recruitment pulse a few years earlier, and again the predicted values did not fit to this peak in frequency at such small sizes. In all other years the predicted catch-at-length approached that of the observed. However, despite the addition of estimation of extra catch into the model improving the fit to CPUE, the fit to length frequency was not improved.

4. Discussion

Given the biogeographical relationship of the Falkland Islands to other areas of the Patagonian shelf it is quite remarkable that a simple age-structured production model based on only Falkland Island data appears to explain the observed CPUE and length composition data so well. Many fish species found around the Falklands are shared stocks between Argentina and the Falkland Islands (Agnew, 2002). A clue to the apparent independence of toothfish in Falkland Island waters is given by the tendency of the species not to move very much as adults (Marlow et al., 2003; Williams et al., 2002), and the fact that two spawning and nursery areas are known; one around Staten Island (Prenski, personal communication) and one between the north eastern edge of Burdwood bank (des Clers et al., 1996) and the Falkland Islands themselves. Thus it seems quite likely that, in general, animals spawning in Falkland Island waters recruit in waters around the Islands, moving to deeper water off-shelf rather than along the shelf.

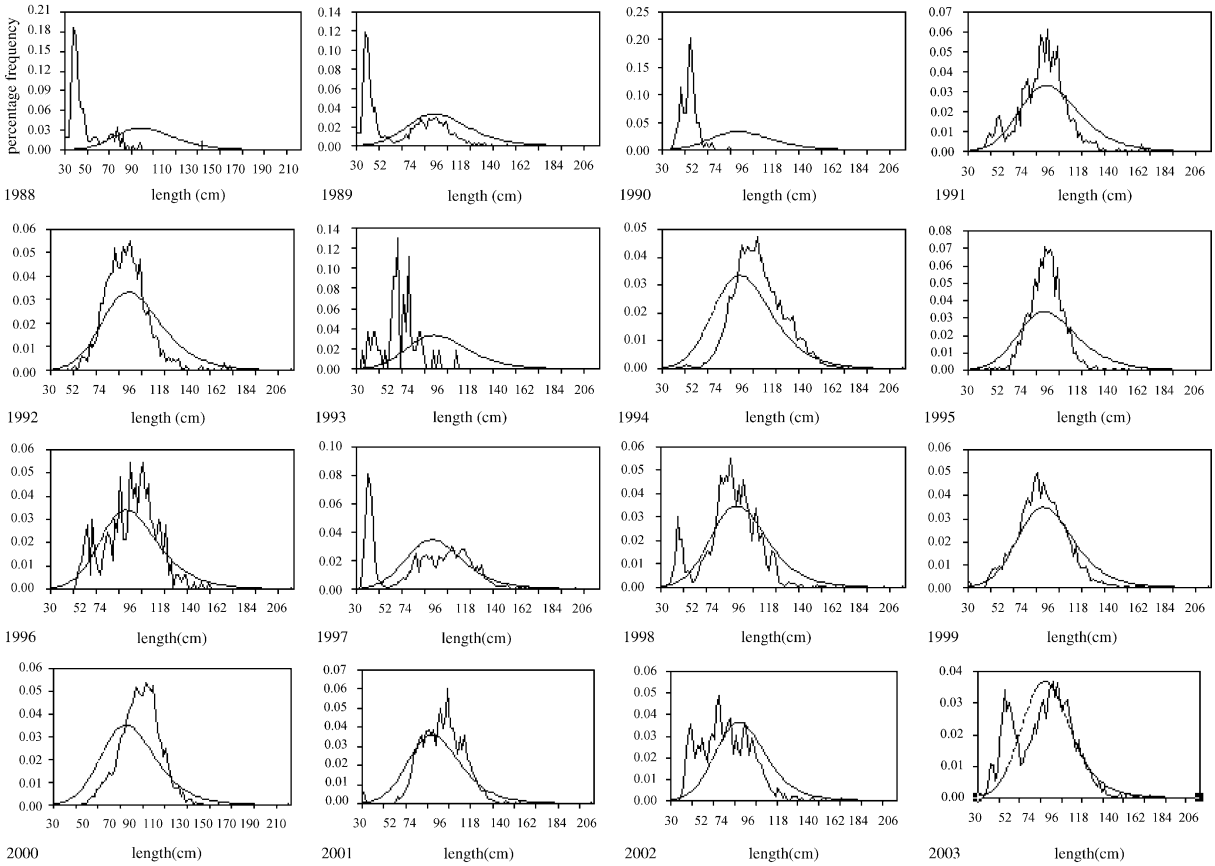

Fig. 4. Observed (solid line) and predicted (dotted line) length frequencies from formulation 1.

What, then, to make of the improved fit of exploitable biomass to the CPUE trend by the addition of almost 5000 additional tonnes of catch in 1995? These extra catches may have resulted from IUU fishing in the Falklands zone, but fishery patrols at this time did not detect a sharp rise in IUU longline activity despite its presence elsewhere in the SW Atlantic (Agnew, 2000). A second possibility is that additional catches taken outside the Falklands zones, but being part of that population, contributed to the decline. When the distribution of recorded toothfish catches from Falklands Longline vessels (Fig. 6) is examined it can be seen that many vessels also operate outside the Falklands Conservation Zones on the high seas around 46 °S and on the north Scotia Ridge. These catches are certainly from the same stock as is fished in Falkland Island waters (Shaw et al., 2004) and, to the extent that they are known (from reports by Falkland Island flagged vessels), they have been included in the total catch figures used in the models. Unfortunately, other than for Falkland licensed vessels it is difficult to estimate the level of catch taken from these areas and catches are likely to have been high in the early 1990s when CPUE was also high.

Other explanations for the rapid decrease in CPUE may be due to changes in other parameters in the model (such as natural mortality, M, and the catchability coefficient, q) but even with further investigation of these parameters, although producing good fits to CPUE similar to those of formulation 2 (Fig. 1d and e) the estimates of q and M are unusually high. For example q is increased by more then 30% in 1994 (to 1.61×10^{-2} compared to 1.22×10^{-2} in remaining years) and 26% in 1995 (1.53×10^{-2}) suggesting that animals were

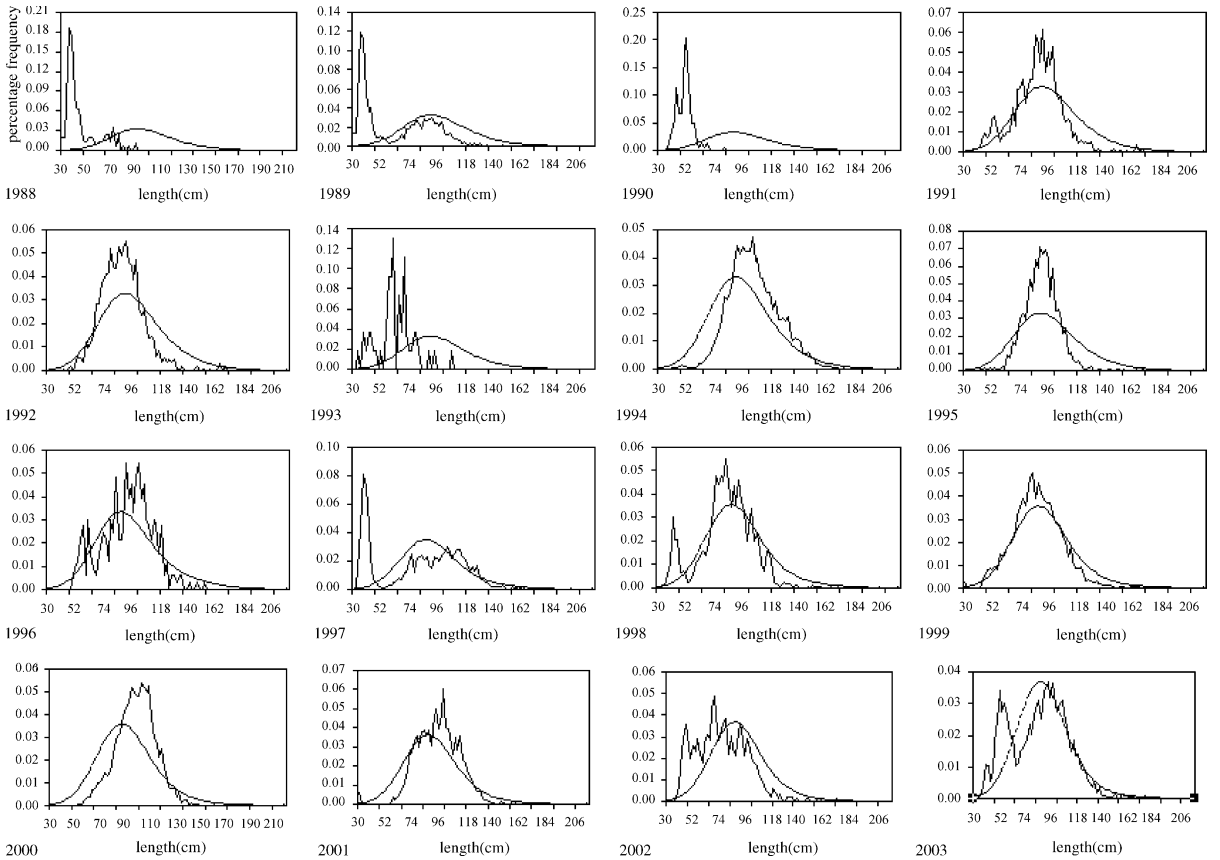

Fig. 5. Observed (solid line) and predicted (dotted line) length frequencies from formulation 3.

more catchable in the early years of the longline fishery and were becoming less so as the fishery developed. This suggests that more fish were accessible and easier to catch in 1994 and 1995 although no additional evidence is available to suggest why this might be so. As for M, in order to produce a radical drop in the population as seen in the CPUE trend, the values of M were greatly increased beyond the boundaries of 0.132–0.198 for CCAMLR Subarea 48.3 (Moreno and Rubilar, 1992; Brandão et al., 2002b; Agnew, 2004). Therefore, it is clear that increases in M cannot be used to explain the rapid decrease in CPUE seen for this fishery.

Formulation 2 results in the highest virgin biomass and the highest current biomass. Formulation 1, using a stock–recruitment relationship, results in a lower estimate of biomass, and although including the estimation of additional catch in 1995 improves the fit (formulation 3) it does not alter these estimates greatly. Thus formulation 2 suggests much higher recruitment than the basic model (the R_0 of formulation 2 being over 1,000,000 individuals greater than formulation 1). This suggests that formulation 2 needs higher recruitment to fit the model than formulation 1 and that recruitment must be increased by 3.85 in order to produce a model that fits as well as the previous formulation.

Future developments of this assessment will focus on understanding toothfish movement and refinement of biological and fishery parameters such as growth, mortality and selectivity. However, these refinements are unlikely to change the general picture of a toothfish stock that is currently between 38 and 46% of its initial stock size of between 32,000 and 56,339 tonnes, with a current spawning stock biomass of approximately

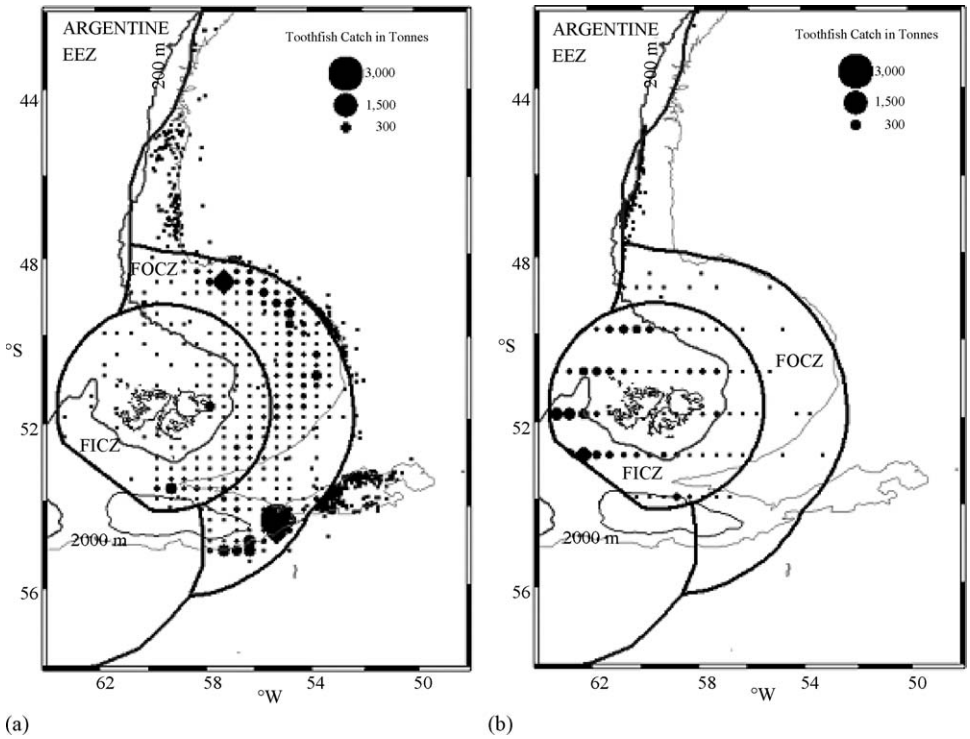

Fig. 6. Distribution of toothfish catches in tonnes from Falkland Island licensed (a) longline (1992–2003) and (b) trawler vessels (1986–2003) fishing in the southwest Atlantic. The concentric circles around the Falkland Islands are the Falkland Islands interim conservation zone (FICZ) and outer conservation zone (FOCZ). The two main islands are East and West Falkland Island.

13,000–26,000 tonnes. MSY is estimated to be between 900 and 2831 tonnes with the most likely being the former. Current catch rates are between 1500 and 2000 tonnes per annum and are likely to be at the limit of sustainable exploitation to be maintained in the long term while managing the fishery effectively.

Acknowledgements

Mr John Barton, Director of the Falkland Islands Fisheries Department provided access to the data used in this study. The work was undertaken under contract to the Falkland Islands Government. The work of Falkland Islands Fisheries Department observers in collecting data from the *Dissostichus eleginoides* fishery over the course of the fishery is gratefully acknowledged as are the comments on the manuscript given by Dr Carl Smith, Dr Alexander Arkhipkin, Dr Vladimir Laptikhovsky and Mr John Barton.

Appendix A. The age-structured production model (ASPM) assessment methodology

A.1. The basic dynamics

The toothfish population dynamics are given by the following equations:

$$N_{y+1,0} = R(B^{\mathrm{sp}}_{y+1}) \tag{A.1}$$

$$N_{y+1,\mathrm{a}+1} = (N_{y,a} - C_{y,a})\,\mathrm{e}^{-M} \tag{A.2}$$

$$N_{y+1,\mathrm{m}} = (N_{y,a} - C_{y,a})\,\mathrm{e}^{-M} + (N_{y,m-1} - C_{y,m-1})\,\mathrm{e}^{-M} \tag{A.3}$$

where $N_{y,a}$ is the number of toothfish of age a at the start of year y, $C_{y,a}$ the number of toothfish of age a taken by the fishery in year y, $R(B^{\mathrm{sp}})$ the Beverton–Holt stock–recruitment relationship described by Eq. (A.12), B^{sp} the spawning biomass

at the start of year y, M the natural mortality rate of the fish (assumed to be age independent), and m the maximum age considered (the plus group of fish aged 21 plus).

Note that in the interests of simplicity this approximates to a pulse fishery at the start of the year. Given that toothfish are relatively long-lived with low natural mortality, such an approximation would seem adequate.

The number of fish of age a caught in year y is given by:

$$C_{y,a} = N_{y,a} S_a F_y \tag{A.4}$$

where F_y is the proportion of the resource above age a harvested in year y, and S_a the commercial selectivity at age a (assumed to be logistic) as described in Eqs. (A.5) and (A.6).

The selectivity for fish younger than 12 years of age is given by:

$$S_a = \frac{1}{1 + \mathrm{e}^{-(a-a_c)/\delta}} \tag{A.5}$$

where a is the age of toothfish caught, a_c the mean age at which 50% of toothfish are retained in the fishing gear, δ the steepness of the selectivity curve.

And the selectivity at age for fish of 12 years of age or older is given by:

$$S_a = \left(\frac{1}{1 + \mathrm{e}^{-(a-a_c)/\delta}} \right) \mathrm{e}^{-\omega(a-a_d)} \tag{A.6}$$

where a_d is the age at which the selectivity vector changes for older fish, ω the steepness of the selectivity curve for older fish.

The mass-at-age is given by the combination of von Bertalanffy growth equation $\ell(a)$ defined by constants ℓ_∞, κ and t_0 and a relationship relating length to mass. Note that ℓ refers to standard length.

$$\ell(a) = \ell_\infty [1 - \mathrm{e}^{-\kappa(a-t_0)}] \tag{A.7}$$

$$w_a = c\ell(a)^d \tag{A.8}$$

where w_a is the mass of fish at age a.

Given knife-edge recruitment to the fishery the total catch by mass in year y is given by:

$$C_y = \sum_{a=0}^{m} w_a C_{y,a} = \sum_{a=0}^{m} w_a S_a F_y N_{y,a} \tag{A.9}$$

which can be re-written as:

$$F_y = \frac{C_y}{\sum_{a=0}^{m} w_a S_a N_{y,a}} = \frac{C_y}{\sum_{a=a_r}^{m} w_a N_{y,a}} \tag{A.10}$$

A.2. Stock–recruitment relationship

The spawning biomass in year y is given by:

$$B_y^{\mathrm{sp}} = \sum_{a=1}^{m} w_a f_a N_{y,a} = \sum_{a=a_m}^{m} w_a N_{y,a} \tag{A.11}$$

where f_a is the proportion of fish at age a that are mature (assumed to be knife edge at age a_m).

The number of recruits at the start of year $y+1$ is assumed to relate to the spawning biomass at the start of year y, B_y^{sp}, by a Beverton–Holt stock recruitment relationship (assuming deterministic recruitment):

$$R(B_{y+1}^{\mathrm{sp}}) = \frac{\alpha B_y^{\mathrm{sp}}}{\beta + B_y^{\mathrm{sp}}} \tag{A.12}$$

The values of the parameters α and β can be calculated given the initial spawning biomass K^{sp} and the steepness of the curve h, using Eqs. (A.13)–(A.17). If the initial (and pristine) recruitment is $R_0 = R(K^{\mathrm{sp}})$, then steepness is the recruitment (as a fraction of R_0) that results when spawning biomass is 20% of its pristine level, i.e.:

$$hR_0 = R(0.2K^{\mathrm{sp}}) \tag{A.13}$$

from which it can be shown that:

$$h = \frac{0.2(\beta + K^{\mathrm{sp}})}{\beta + 0.2K^{\mathrm{sp}}} \tag{A.14}$$

Rearranging Eq. (A.14) gives:

$$\beta = \frac{0.2K^{\mathrm{sp}}(1-h)}{h - 0.2} \tag{A.15}$$

In the absence of exploitation, the population is assumed to be in equilibrium. Therefore R_0 is equal to the loss in numbers due to natural mortality when $B^{\mathrm{sp}} = K^{\mathrm{sp}}$, and hence:

$$\gamma K^{\mathrm{sp}} = R_0 = \frac{\alpha K^{\mathrm{sp}}}{\beta + K^{\mathrm{sp}}} \tag{A.16}$$

where

$$\gamma = \left\{ \sum_{a=1}^{m-1} w_a f_a \, \mathrm{e}^{-M_a} + \frac{w_m f_m \, \mathrm{e}^{-M_m}}{1 - \mathrm{e}^{-M}} \right\}^{-1} \quad \text{(A.17)}$$

A.2.1. Past stock trajectory

Given a value for the pre-exploitation spawning biomass (K^{sp}) of toothfish, and the assumption that the initial age structure is at equilibrium, it follows that:

$$K^{\mathrm{sp}} = R_0 \left(\sum_{a=1}^{m-1} w_a f_a \, \mathrm{e}^{-M_a} + \frac{w_m f_m \, \mathrm{e}^{-M_m}}{1 - \mathrm{e}^{-M}} \right) \quad \text{(A.18)}$$

which can be solved for R_0.

The initial numbers at each age a for the trajectory calculations, corresponding to the deterministic equilibrium are given by:

$$N_{0,a} = \begin{cases} R_0 \, \mathrm{e}^{-M_a} & 0 \le a \le m-1 \\ \dfrac{R_0 \, \mathrm{e}^{-M_a}}{1 - \mathrm{e}^{-M}} & a = m \end{cases} \quad \text{(A.19)}$$

Numbers-at-age for subsequent years are then computed by mean of Eqs. (A.1)–(A.4) and (A.9)–(A.12) under the series of annual catches given. In cases where Eq. (A.10) yields a value of $F_y > 1$ for a future year, i.e. the available biomass is less then the proposed catch for that year, F_y is restricted to 0.9, and the actual catch considered to be taken will be less than the proposed catch.

The model estimate of the exploitable component of the biomass is given by:

$$B_y^{\mathrm{exp}} = \sum_{a=0}^{m} w_a S_a N_{y,a} = \sum_{a=a_r}^{m} w_a N_{y,a} \quad \text{(A.20)}$$

A.3. The likelihood function

The age-structured production model (ASPM) is fitted to the GLM standardised CPUE to estimate model parameters. The likelihood is calculated assuming that the observed CPUE abundance index is lognormally distributed about its expected value:

$$l_y = \hat{l}_y \, \mathrm{e}^{\varepsilon_y} \quad \text{or} \quad \varepsilon_y = \ln(l_y) - \ln(\hat{l}_y) \quad \text{(A.21)}$$

where l_y is the standardised longline CPUE series index for year y, $\hat{l}_y = q\hat{B}_y^{\mathrm{exp}}$ the corresponding model estimate, where, $\hat{B}_y^{\mathrm{exp}}$ is the model estimate of exploitable biomass of the resource for year y, and $\hat{q}$ the catchability coefficient for the standardised commercial longline CPUE abundance indices, whose maximum likelihood estimate is given by:

$$\ln \hat{q} = \frac{1}{n} \sum_{y} (\ln l_y - \ln \hat{B}_y^{\mathrm{exp}}) \quad \text{(A.22)}$$

where n is the number of data points in the standardised CPUE abundance series. ε_y is normally distributed with mean zero and standard deviation σ (assuming homoscedasticity of residuals), whose maximum likelihood estimate is given by:

$$\hat{\sigma} = \sqrt{\frac{1}{n} \sum_{y} (\ln l_y - \ln(\hat{q}\hat{B}_y))^2} \quad \text{(A.23)}$$

The negative log likelihood function (ignoring constants) which is minimised in the fitting procedure is thus:

$$-\ln L = \sum_{y} \left[\frac{1}{2(\sigma)^2} (\ln l_y - \ln(qB_y))^2 \right] + n(\ln \sigma) \quad \text{(A.24)}$$

The estimable parameters of this model are q, K^{sp} and σ (where K^{sp} is the pre-exploitation mature biomass) and the parameters a_c, δ, and ω within the logistic selectivity.

Confidence intervals for some of the parameters estimated have been evaluated using the likelihood profile method, or the Hessian-based approximation.

A.4. Extensions to incorporate catch-at-length information

The above model estimates the catch-at-age ($C_{y,a}$) in numbers realised by the fishery each year from Eq. (A.4). These can then be converted into proportions of the catch of age a:

$$p_{y,a} = \frac{C_{y,a}}{\sum_{a'} C_{y,a'}} \quad \text{(A.25)}$$

Using the von Bertalanffy growth Eq. (A.7), these proportions-at-age can be converted to proportions-at-length under the assumption that the distribution of length-at-age remains constant over time:

$$p_{y,\ell} = \sum_{a} p_{y,a} A_{a,\ell} \quad \text{(A.26)}$$

where $A_{a,\ell}$ is the proportion of fish of age a that fall in length group ℓ. Not that therefore:

$$\sum_{\ell} A_{a,\ell} = 1 \quad \text{for all ages } a \tag{A.27}$$

The A matrix has been calculated here under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$\ell(a)\ N^*[\ell_\infty\{1 - \mathrm{e}^{-\kappa(a-t_0)}\}; \theta(a)^2] \tag{A.28}$$

where N^* is the normal distribution truncated at ± 3 standard deviations (to avoid negative values), and $\theta(a)$ the standard deviation of length-at-age a, which is modelled here to be proportional to the expected length-at-age a, i.e.:

$$\theta(a) = \beta\ell_\infty\{1 - \mathrm{e}^{-\kappa(a-t_0)}\} \tag{A.29}$$

with β a parameter estimated in the model fitting process.

Note that since the model of the population's dynamics is based upon a 1-year time step, the value of β and hence the $\theta(a)$s estimated will reflect not only the real variability of length-at-age, but also the "spread" that arises from the fact that fish in the same annual cohort are not all spawned at exactly the same time, and that catching takes place throughout the year so that there are differences in the age (in terms of fractions of a year) of fish allocated to the same cohort.

Model fitting is effected by adding the following term to the negative log-likelihood of Eq. (A.24):

$$-\ln L_{\text{len}} = w_{\text{len}} \sum_{y,\ell} \left\{ \ln\left[\frac{\sigma_{\text{len}}}{\sqrt{p_{y,l}}}\right] + \left(\frac{p_{y,\ell}}{(2\sigma^2_{\text{len}})}\right)\left[\ln p^{\text{obs}}_{y,\ell} - \ln p_{y,\ell}\right]^2 \right\} \tag{A.30}$$

where $p^{\text{obs}}_{y,\ell}$ is the proportion by number of the catch in year y in length group ℓ, and σ_{len} has a closed form maximum likelihood estimate given by:

$$\hat{\sigma}^2_{\text{len}} = \sum_{y,\ell} p_{y,\ell} \frac{\left[\ln p^{\text{obs}}_{y,\ell} - \ln p_{y,\ell}\right]^2}{\sum_{y,\ell} 1} \tag{A.31}$$

Eq. (A.30) makes the assumption that proportions-at-length data are lognormally distributed about their model-predicted values. The associated variance is taken to be inversely proportional to $p_{y,\ell}$ to down weight contributions from expected small proportions which will correspond to small observed sample sizes. This adjustment is of the form to be expected if a Poisson-like sampling variability component makes a major contribution to the overall variance. Given that overall sample sizes for length distribution data differ quite appreciably from year to year subsequent refinements of this approach may need to adjust the variance assumed for Eq. (A.30) to take this into account. The w_{len} weighting factor may be set at a value less than 1 to down weight the contribution of the catch-at-length data to the overall negative log-likelihood compared to that of the CPUE data in Eq. (A.24). The reason that this factor is introduced is that the $p^{\text{obs}}_{y,\ell}$, data for a given year frequently show evidence of strong positive correlation, and so are not as informative as the independence assumption underlying the form of Eq. (A.30) would otherwise suggest. In the practical application of Eq. (A.30), length observations were grouped by 2 cm intervals, with minus- and plus-groups specified below 40 and above 220 cm, respectively, to ensure $p^{\text{obs}}_{y,\ell}$, values in excess of about 2% for these cells.

References

Agnew, D.J., 2000. The illegal and unregulated fishery for toothfish in the Southern Ocean, and the CCAMLR catch documentation scheme. Mar. Policy 24, 274–361.

Agnew, D.J., 2002. Critical aspects of the Falkland Islands pelagic ecosystem: distribution, spawning and migration of pelagic animals in relation to oil exploration. Aquat. Conserv.: Mar. Freshw. Ecosyst. 12, 39–50.

Agnew, D.J., 2004. Fishing South: The History and Management of South Georgia Fisheries. The Penna Press, St. Albans.

Agnew, D.J., Heaps, L., Jones, C., Watson, A., Pearce, J., 1999. Depth distribution and spawning pattern of *Dissostichus eleginoides* at South Georgia. CCMALR Sci. 6, 19–36.

Agnew, D.J., Kirkwood, G., 2004. Assessment of the status of the toothfish stock in Subarea 48.3. CCAMLR, WG-FSA-04/82 (CCAMLR documents may be obtained by contacting the CCAMLR Secretariat at CCAMLR, PO Box 7002, Tasmania, Australia, or CCAMLR@CCAMLR.org who will contact the authors).

Baranowski, R., Kirkwood, G., des Clers, S., 1995. 1995 Assessment of the Falklands longline fishery for toothfish, *Dissostichus eleginoides*. CCAMLR document WG-FSA-95/26 (CCAMLR documents may be obtained by contacting the CCAMLR Secretariat at CCAMLR, PO Box 7002, Tasmania, Australia, or CCAMLR@CCAMLR.org who will contact the authors).

Brandão, A., Butterworth, D.S., Watkins, B.P., Miller, D.G.M., 2002a. A first attempt at an assessment of the Patagonian toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands EEZ. CCAMLR Sci. 9, 11–32.

Brandão, A., Butterworth, D.S., Watkins, B.P., Staverees, L., 2002b. An updated assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity and extensions taking commercial catch-at-length data into account. CCAMLR document WG-FSA-02/76 (CCAMLR documents may be obtained by contacting the CCAMLR Secretariat at CCAMLR, PO Box 7002, Tasmania, Australia, or CCAMLR@CCAMLR.org who will contact the authors).

CCAMLR, 2002. Report of the Fish Stock Assessment Working Group. CCAMLR, Hobart (CCAMLR documents may be obtained by contacting the CCAMLR Secretariat at CCAMLR, PO Box 7002, Tasmania, Australia, or CCAMLR@CCAMLR.org who will contact the authors).

Khalid, A.J., de la Mare, W.K., 1996. A generalised yield model for evaluating yield and the long term status of fish stocks under conditions of uncertainty. CCAMLR Sci. 3, 31–54.

des Clers, S., Nolan, C.P., Baranowski, R., Pompert, J., 1996. Preliminary stock assessment of the Patagonian toothfish longline fishery around the Falkland Islands. J. Fish Biol. 49 (Suppl. A), 145–156.

DeWitt, H., Heemstra, P.C., Gon, O., 1990. Nototheniidae. In: Gon, O., Heemstra, P.C. (Eds.), Fisheries of the Southern Ocean. J.L.B. Smith Institute of Ichthyology, Grahamstown, pp. 279–311.

Eastman, J.T., 1993. Antarctic Fish Biology: Evolution in a Unique Environment. Academic Press, San Diego.

Everson, I., Murray, A., 1999. Size at sexual maturity of Patagonian toothfish. CCAMLR Sci. 6, 37–46.

FAO, 2002. Fishery Statistics: Capture Production 2000. FAO, Rome.

FAO, 2004. Fishery Statistics: Capture Production 2002. FAO, Rome.

Falkland Islands Government, 2004. Fishery Department Fisheries Statistics, vol. 8. FIG Fisheries Department, Stanley, Falkland Islands.

Froese, R., Pauly, D. (Eds.), 2005. Fishbase. World Wide Web Electronic Publication. www.fishbase.org, version (02/2005).

González, E.P., García, M.A. 2001. Changes in fleet capacity and ownership of harvesting rights in the fishery for Patagonian toothfish in Chile. In: Case Studies on the Effects of Transferable Fishing Rights on Fleet Capacity and Concentration of Quota Ownership. FAO Fish. Tech. Pap. 412, 238 pp. (CCAMLR documents may be obtained by contacting the CCAMLR Secretariat at CCAMLR, PO Box 7002, Tasmania, Australia, or CCAMLR@CCAMLR.org who will contact the authors).

Kellerman, A., 1990. Catalogue of early life stages of Antarctic Notothenioid fishes. Berichte zur Polarforschung 67, 45–136.

Marlow, T.M., Agnew, D.J., Everson, I., 2003. Movement and growth of tagged toothfish around South Georgia and Shag Rocks (Subarea 48.3). CCAMLR Sci. 10, 101–111.

Møller, P.R., Nielsen, J.G., Fossen, I., 2003. Fish migration: Patagonian toothfish found off Greenland. Nature 421, 599.

Moreno, C.A., Rubilar, P.S., 1992. Remarks on the natural mortality of *Dissostichus eleginoides* in Subarea 48.3. In: Selected Scientific Papers, 1992 (SC-CAMLR-SSP/9). CCAMLR, Hobart, pp. 21–30 (CCAMLR documents may be obtained by contacting CCAMLR, PO Box 7002, Tasmania, Australia or CCAMLR@CCAMLR.org who will contact the authors).

North, A.W., 2002. Larval and juvenile distribution and growth of Patagonian toothfish around South Georgia. Ant. Sci. 14, 25–31.

Shaw, P.W., Arkhipkin, A.I., Al-Khairulla, H., 2004. Genetic structuring of Patagonian toothfish populations in the southwest Atlantic Ocean: the effect of the Antarctic Polar Front and deep-water troughs as barriers to genetic exchange. Mol. Ecol. 13, 3293–3303.

Tuck, G.N., de la Mare, W.K., Hearn, W.S., Williams, R., Smith, A.D.M., He, X., Khalid, A., 2003. An exact time of release and recapture stock assessment model with an application to Macquarie Island Patagonian toothfish (*Dissostichus eleginoides*). Fish. Res. 63, 179–191.

Williams, R., Tuck, G.N., Khalid, A., Lamb, T., 2002. Movement, growth and available abundance to the fishery of *Dissostichus eleginoides* Smitt, 1898 at Heard Island derived from tagging experiments. CCAMLR Sci. 9, 33–48.

Yau, C., Collins, M.A., Bagley, P.M., Everson, I., Nolan, C.P., Priede, I.G., 2001. Estimating the abundance of Patagonian toothfish *Dissostichus eleginoides* using baited cameras: a preliminary study. Fish. Res. 51, 403–412.